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TITLE: IMPROVED TISSUE SUPPORTING DEVICES

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IMPROVED TISSUE SUPPORTING DEVICES

Background of the Invention

This invention relates to tissue supporting devices in general and most particularly to vascular stents for placement in blood vessels. A primary feature of the devices of this invention is that they are expandable within the body.

In the past, such devices have been provided for implantation within body passageways. These devices have been characterized by the ability to be enlarged radially, often having been introduced into the desired position in the body as by percutaneous techniques or surgical techniques.

These devices are either expanded mechanically, such as by expansion of a balloon positioned inside the device, or are capable of releasing stored energy to self-expand themselves within the body.

The materials which have been used to make up these devices have included ordinary metals, shape memory alloys, various plastics, both biodegradable and not, and the like.

This invention is concerned with the use of these materials in a new multiple component arrangement which allows for initial self-expansion and subsequent deformation to a final enlarged diameter in the body.

Balloon expandable stents do not always expand uniformly around their circumference. As a result, healing may not take place in a consistent manner. If the stent is coated or covered, non-uniform expansion may tear the covering or coating. Additionally, long stents of this type may require long balloons which can be difficult to handle, difficult to size, and may not offer ideal performance in tortuous passages in blood vessels and the like.

Thus, when addressing such issues, self-expandable stents have been thought to be generally more desirable. Unfortunately, one cannot control the degree of expansion and hence the degree of embedment in the vessel wall. It has been determined that a stent must be embedded to some degree to be clinically satisfactory.

The stents of the present invention provide the best features of both of these types of stents without their drawbacks.

Summary of the Invention

The tissue supporting devices of this invention are generally cylindrical or tubular in overall shape and of such a configuration as to allow radial expansion for enlargement. They are often referred to herein in the general sense as "stents".

5 Furthermore, the devices are comprised of at least one component, element, constituent or portion which exhibits a tendency to self-expand the device to an expanded size and at least one other component, element, constituent or portion which is deformable so as to allow an external force, such as a balloon positioned within the body of the device, to further expand it to a final, larger desired expanded size. The

10 terms "component", "element", "constituent" and "portion" are often referred to herein collectively as "portion".

Preferably, the devices of the invention are made of metal and most preferably of shape memory alloys.

In one embodiment, a first portion is a resilient spring-like metal for

15 self-expansion and a second portion is a deformable metal for final sizing. In a more preferred shape memory embodiment, a first portion is a self-expanding austenitic one and a second is a martensitic one capable of deformation. In the case of shape memory embodiments the "portions" may be discrete or merely different phases of an alloy.

20 The most preferred embodiment of the invention is a stent, preferably of shape memory alloy. The most preferred shape memory alloy is Ni-Ti, although any of the other known shape memory alloys may be used as well. Such other alloys include: Au-Cd, Cu-Zn, In-Ti, Cu-Zn-Al, Ti-Nb, Au-Cu-Zn, Cu-Zn-Sn, Cu-Zn-Si, Cu-Al-Ni, Ag-Cd, Cu-Sn, Cu-Zn-Ga, Ni-Al, Fe-Pt, U-Nb, Ti-Pd-Ni, Fe-Mn-Si, and

25 the like. These alloys may also be doped with small amounts of other elements for various property modifications as may be desired and as is known in the art.

The invention will be specifically described hereinbelow with reference to stents, a preferred embodiment of the invention although it is broadly applicable to tissue support devices in general.

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Brief Description of the Figures

Figure 1 is a braided stent according to one embodiment of this invention.

Figure 2 is a graph showing the martensitic/austenitic temperature transformation curve and the superelastic area of a shape memory alloy.

Figures 3 is an end view of a layered stent having two discrete components according to one aspect of this invention.

Figures 4a and 4b are graphs showing the martensitic/austenitic temperature transformation curves of the layers in the stent of Figure 3.

Figure 5a and 5b are views of another embodiment of the invention comprised of alternating rings of shape memory alloy.

Figure 6 is a showing of a stent fragment of a braided version of a shape memory stent of this invention.

Figure 7 is a graph showing a temperature window for a shape memory alloy to be used in yet another stent version of this invention.

Figure 7a is a graph showing expansion of a stent with temperature.

Figure 7b is a graph of the same type, the stent having been cold-worked.

Figure 7c is a graph of the same type, the stent having had pseudoelastic prestraining.

Figure 7d is a graph of the same type, the stent having amnesia inducement.

Figures 8-11 show various expandable configurations (closed and open) illustrated in fragment which may be used in the stents of this invention. Figures 9a and 9b show a preferred embodiment of an articulated stent.

Figure 12 shows another version of an expandable stent of the invention.

Figure 13 shows yet another version of a stent which may be used with the invention.

Figure 14 is a schematic showing of a braided stent made up of a plurality of strands.

Figure 15 is a detail of a single strand from the stent of Figure 14 showing that the strand is made up of a plurality of wires of two different types.

Figure 16 is a cross-sectional view taken along line 16-16 of Figure 15 showing the two different types of wire.

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Detailed Description of the Invention

Preferred embodiments of this invention are described below with particular reference to the accompanying drawing Figures.

Referring first to the embodiment shown in Figure 1, a stent 10 is

10   shown comprised of braided or interwoven metal strands 12 and 14. Strands 12 are of a resilient spring-like metal such as spring steel, Elgiloy for example. Preferably, strands 12 are spirally extending in the same direction, spiraling to the right as seen in Figure 1. Strands 14 are of a deformable or annealed metal such as stainless steel and are preferably spiraled in the opposite direction as strands 12, as shown in Figure 1.

15   Given such a stent construction of two components *i.e.*, strands 12 and 14, it can be seen that stent 10 may be readily loaded on a catheter as by placing it over an uninflated balloon on a balloon catheter and compressing it tightly around the balloon and then placing a sheath over the stent to hold it in place during the transluminal placement procedure. Once in place, the sheath is removed, for example

20   slid back, to expose the stent, allowing it to self-expand by force of the resilient strands 12 to substantially assume a self-expanded shape/size. Some self-expansion may be restrained if held back by strands 14. To finally adjust the size of the stent, the balloon may be expanded by inflation from within the stent to exert an outward radial force on the stent and further enlarge it by stretching and deforming the

25   deformable metal of strands 14. This may be aided by building into strands 14, a series of readily deformable structures or means such as bends or kinks 16 as shown in Figure 1. It can be seen that a permanent adjustable size beyond the self-expanded size may be obtained with this embodiment. It is to be noted that many configurations other than braided may be readily devised to take advantage of this two component

30   concept, including various of the subsequent configurations described hereinbelow. Also, it should be noted that, although not preferred, the stent may be initially deployed without a balloon; the balloon following on a separate catheter.

Referring now to subsequent features, other preferred embodiments of the invention will be described which make use of shape memory alloys and some of their unique properties, primarily their special types of deformation i.e., shape memory deformation in martensite and/or superelastic deformation in austenite.

5　　　　The term "superelasticity" is used to describe the property of certain shape memory alloys to return to their original shape upon unloading after a substantially deformation while in their austenitic state. Superelastic alloys can be strained while in their austenitic state more than ordinary spring materials without being plastically deformed. This unusually large elasticity in the austenitic state is

10　also called "pseudoelasticity", because the mechanism is nonconventional in nature, or is also sometimes referred to as "transformational superelasticity" because it is caused by a stress induced phase transformation. Alloys that show superelasticity also undergo a thermoelastic martensitic transformation which is also the prerequisite for the shape memory effect. Superelasticity and shape memory effects are therefore

15　closely related. Superelasticity can even be considered part of the shape memory effect.

The shape memory and superelasticity effects are particularly pronounced in Ni-Ti alloys. This application will therefore focus on these alloys as the preferred shape memory alloys. The shape memory effect in Ni-Ti alloys has

20　been described many times and is well known.

In near-equiatomic Ni-Ti alloys, martensite forms on cooling from the body centered cubic high temperature phase, termed austenite, by a shear type of process. This martensitic phase is heavily twinned. In the absence of any externally applied force transformation takes place with almost no external macroscopic shape

25　change. The martensite can be easily deformed by a "flipping over" type of shear until a single orientation is achieved. This process is also called "detwinning".

If a deformed martensite is now heated, it reverts to austenite. The crystallographic restrictions are such that it transforms back to the initial orientation

30　thereby restoring the original shape. Thus, if a straight piece of wire in the austenitic condition is cooled to form martensite it remains straight. If it is now deformed by bending, the twinned martensite is converted to deformed martensite. On heating, the

transformation back to austenite occurs and the bent wire becomes straight again. This process illustrates the shape memory deformation referred to above.

The transformation from austenite to martensite and the reverse transformation from martensite to austenite do not take place at the same temperature.

5   A plot of the volume fraction of austenite as a function of temperature provides a curve of the type shown schematically in Fig. 2. The complete transformation cycle is characterized by the following temperatures: austenite start temperature (A_s), austenite finish temperature (A_f), both of which are involved in the first part (1) of an increasing temperature cycle and martensite start temperature (M_s) and martensite

10   finish temperature (M_f), both of which are involved in the second part (2) of a decreasing temperature cycle.

Figure 2 represents the transformation cycle without applied stress. However, if a stress is applied in the temperature range between A_s and M_d, martensite can be stress-induced. Stress induced martensite is deformed by

15   detwinning as described above. Less energy is needed to stress induce and deform martensite than to deform the austenite by conventional mechanisms. Up to about 8% strain can be accommodated by this process (single crystals of specific alloys can show as much as about 25% pseudoelastic strain in certain directions). As austenite is the thermodynamically stable phase at temperatures between A_s and M_d under no-load

20   conditions, the material springs back into its original shape when the stress is no longer applied.

It becomes increasingly difficult to stress-induce martensite at increasing temperatures above A_f. Eventually, it is easier to deform the material by conventional mechanisms (movement of the dislocation, slip) than by inducing and

25   deforming martensite. The temperature at which martensite can no longer be stress-induced is called M_d. Above M_d, Ni-Ti alloys are deformed like ordinary materials by slipping.

Additional information regarding shape memory alloys is found in the following references, all of which are incorporated fully herein by reference:

30   *"Super Elastic Nickel-Titanium Wires"* by Dieter Stöckel and Weikang Yu of Raychem Corporation, Menlo Park, California, copy received November 1992;

Metals Handbook, Tenth Edition, Vol. 2, *Properties and Selection: Nonferrous Alloys and Special-Purpose Materials*, "Shape Memory Alloys" by Hodgson, Wu and Biermann, pp. 897 - 902; and, In Press, *Titanium Handbook*, ASM (1994), Section entitled

5 *"Structure and Properties of Ti-Ni Alloys* by T.W. Duerig and A.R. Pelton.

Since the most preferred shape memory alloy is Ni-Ti, the martensitic state of this alloy may be used to advantage in the two component concept of this invention.

10 For example, with reference to Figure 3, a layered construction may be provided in a stent 30 (shown in end view) which is generally a hollow cylindrical or tubular body in shape but which may be formed in a wide variety of specific configurations or patterns to foster radial expansion of the body as exemplified in Figures 1, 5, 6 and in subsequent Figures 8-11.

15 Stent 30 is comprised of at least two layers 32 and 34, one of which 32 is a Ni-Ti alloy (50.8 atomic wt. % Ni, balance Ti, transition temperature of $A_f=0°$ C) and normally in the austenitic state, the other of which 34 is a Ni-Ti (49.4 atomic wt. % Ni, balance Ti, transition temperature $A_f = 60°$ C) and normally in the martensitic state. Preferably, the inner layer is 32 and the outer layer is 34.

20 However, this may be reversed and also a plurality of layers, alternating or otherwise, may be utilized in this particular embodiment.

Stent 30 is made to a fabricated size and shape (parent shape) which provides austenitic layer 32 its parent shape and size *i.e.*, its superelastic high temperature shape and size. Obviously, in its as fabricated condition, the Ni-Ti alloy

25 of austenitic layer 32 is selected so as to have a transition temperature range between its austenitic and martensitic states which is lower than body temperature as to ensure that in the body and at body temperatures the austenitic state will always prevail.

On the other hand, martensitic layer 34 is of a Ni-Ti alloy having a transition temperature range significantly greater than body temperature so as to

30 ensure that under body conditions the martensitic state will always prevail and the alloy will never transform to austenite in stent use. This is shown in the graphs of Figure 4a and 4b which demonstrate the relative transition temperatures of layers 32

and 34, respectively for purposes of this invention. It can be seen from these graphs that the normal condition of layer 32 (Figure 4a) at body temperatures and higher is the austenitic state while the normal condition of layer 34 (Figure 4b) at body temperatures is martensitic.

5   To manufacture the layered construction, one may make the austenitic portion with any standard metallurgical technique and vapor deposit the martensitic portion on its surface. Other manufacturing techniques such as diffusion bonding, welding, ion beam deposition, and various others will be apparent to those familiar with this art.

10   Such a stent may be compressed or constrained (deformed to a small diameter) onto a balloon catheter as described for the previous embodiment and captured within a sheath. During the constrainment, austenitic layer 32 may stress induce to a martensitic state. In the alternative, the stent may be cooled below the transition temperature of layer 32 to facilitate its deformation and constrainment.

15   Martensitic layer 34 merely undergoes deformation. Thus the stent may be "loaded" onto a balloon catheter. However, with temperature changes occurring up to body temperature, layer 32 will remain martensite until the constraint is removed. When released in place in the body, stent 30 will expand to a percentage of its self-expanded size and shape due to the transformation of layer 32 from martensite to austenite at

20   which point the balloon may be used to radially expand the stent to a greater permanent diameter by deforming martensitic layer 34. On the other hand, initial deployment can take place without a balloon which may be separately inserted after deployment.

           The two component concept of the invention in the layered embodiment

25   of Figure 3 requires both the martensitic and austenitic phase characteristics of shape memory alloy(s) in the two discrete components 32 and 34.

           Preferably, the stent is fabricated in such a way that the austenitic layer 32 tends to self-expand stent 30 to a predetermined fabricated diameter (parent shape). The martensitic layer 34 tends to hold back this self-expansion, preventing full

30   expansion. For example, the stent may only be able to self-expand to 75% of its full possible diameter (as determined by the austenitic layer). Therefore, expansion beyond 75% is accomplished by an applied external force, as by the balloon inside the

stent. It is suggested that the stent not be expanded beyond its normal fabricated diameter for the austenitic layer 32 will have the tendency of making the stent diameter smaller as it tries to recover its fabricated diameter (parent shape). If the stent is subjected to a temperature above body temperature and above the transition

5   temperature of the martensitic layer (which is clinically unlikely), the stent will self-expand to the fabricated diameter only. Depending on design size there are thus provided permanent stents capable of fulfilling any needed range of sizes with an adjustable sizing capability.

As is known in the art, the desired properties of the shape memory

10   alloys required for use in this invention may be obtained by alloy composition and working and heat treatment of the alloys, in various combinations or singly.

Manufacturing techniques influence the phase characteristics of the material. Alloy composition, work history, and heat treatment all influence the final characteristics. At a specific operating temperature, say body temperature, the

15   austenite phase material will have a transition temperature below body temperature (i.e., $A_f=0°C$). The material is capable of taking high strains and recovering after the load is released. The martensite phase material will have a higher transition temperature than body temperature (i.e., $A_f=60°C$), and is characteristically soft and pliable and retains the deformed shape after load removal. This martensite

20   deformation is caused by detwinning, not the typical plastic deformation, or yielding, of crystal slip.

With reference to Figures 5 and 6, other stent constructions are shown which are similar to the layered version of Figure 3 in so far as utilization of the two component concept of this invention is concerned.

25   Figure 5a and 5b shows a stent 50 made up of alternating expandable rings 52 and 54 of austenitic and martensitic alloys, respectively, analogous to layers 32 and 34 of the Figure 3 embodiment. Rings 52 and 54 for example are interconnected by strut members 56 which may be of any material capable of rigidly holding the rings together. Other interconnector means may be used. As can be seen

30   in Figure 5b, the placement of strut members 56 does not require them to take part in the radial expansion of the stent and they can therefore be of a relatively ordinary material such as stainless steel.

Referring now to Figure 6, a braided or interwoven construction is shown similar in construction to that of the embodiment of Figure 1. In this embodiment, strands 62 extending to the right in Figure 6 are an alloy in the austenitic state whereas strands 64 extending to the left in Figure 6 are an alloy in the

5   martensitic state.

Referring now to the graph of Figure 7, it is demonstrated that the two component concept of the invention may be embodied in two phases, i.e., components of a single shape memory alloy and need not be in the form of two discrete components such as layers, members, wires, etc. In the graph of Figure 7, it can be

10   seen that an alloy composition can be selected such that it has a phase transition temperature window that bounds the proposed operating temperatures of the stent, such as the normal body temperature range. Within this transitional window or zone, the material undergoes the phase transition and is effectively compositionally comprised of a ratio of austenitic to martensitic phase depending on the temperature of

15   the stent. This ratio should be selected so as to provide sufficient radial force from the austenite phase while still allowing for further expansion of the martensite phase with a mechanical expansion means such as a balloon. Selecting body temperature as the operating temperature, a Ni-Ti alloy of about 50/50 atomic wt. % composition (range about 49/51%) will provide an acceptable "window" for this embodiment, the

20   two components are the austenite and martensite phases of the nitinol.

The method of making a stent may be described as follows. Age the shape memory material (Ni Ti) until body temperature falls somewhere within the transformation window. Therefore the stent will not fully recover to its high temperature shape at body temperature. An example of this technique is described

25   below.

A stent of tubular 50.8% Ni balance Ti was prepared having a 1.5 mm diameter. It was substantially all austenite at room temperature, the A_f being about 15-20°C and therefore being superelastic at room temperature. The stent was cooled to below room temperature to form substantially all martensite and mechanically

30   expanded to 4.7 mm in diameter. It was maintained at the 4.7 mm in diameter and heat treated at 500°C for 30 minutes and water quenched. Finally, it was again cooled to below room temperature to form substantially all martensite and compressed

to a diameter of 1.5 mm. After deployment and at body temperature the stent has a diameter of 3.5 mm. At about 70% of full expansion, i.e., about 40°C it had a diameter of 4.5 mm and at 42°C it had a fully expanded diameter of 4.7 mm.

5   This method works fairly well, but due to the slope of the temperature versus diameter plot being extremely vertical at body temperature, a small change in body temperature, or manufacturing control, can have a large impact on the actual self expansion diameter. As can be seen from Figure 7, the slope of the line between A_f and A_s is rather steep with small changes in temperature leading to large changes in percent austenite and consequently large changes in diameter of a stent made of such

10   an alloy. Figure 7a shows a temperature versus diameter plot. Three methods of modifying the slope of the line on the temperature versus diameter graph are cold work, pseudoelastic prestraining, and amnesia inducement, illustrated in Figures 7b, 7c and 7d, respectively.

COLD WORK

15   Residual cold work in nitinol draws out or masks the point of A_f on the diameter versus the temperature curve. This is seen by the sluggish increase in diameter as temperature increases in the last 20-30% of recover. By utilizing the effects of cold work, the effects of temperature change on diameter can be reduced in the last 20 to 30% of stent expansion. Shown in Figure 7b is an example of a

20   temperature versus diameter plot for a cold worked part. Figure 7a above shows an example of a part without cold work.

PSEUDOELASTIC PRESTRAINING

Utilizing the effects of pseudoelastic prestraining (S. Eucken and T.W. Duerig, *ACTA Metal*, Vol. 37, No. 8, pp 2245-2252, 1989) one can create two

25   distinct plateaus in the stress-strain behavior. This difference in stress strain behaviors can be directly linked to two distinct A_f temperatures for the two plateaus. By placing the transition between the two plateaus at the transition from self expanding to balloon expanding, i.e., 70%, one can control the characteristics of the stent at body temperature. The goal would be to place the A_f temperature for the first

30   plateau (from maximum compression to 70% expansion) below body temperature such that the stent has self expanding characteristics. The A_f temperature for the second plateau would be above body temperature such that there is no additional self

expansion in this region (70 to 100% expansion) a mechanical device, like a balloon, can then be used to custom size the stent between 70% and 100% of the high temperature shape. Results of such a technique is shown in Figure 7c.

AMNESIA INDUCEMENT

5   One of the characteristics of nitinol is cycle amnesia. This was also discussed about in the article referred to immediately above. As nitinol is cycled from its heat set shape as shown in Figure 7d, there is an increase in the amount of amnesia to recover to the heat set shape with each cycle. As long as this amnesia is not caused by permanent plastic deformation, the amnesia can be removed by heating the part

10   above M_d. This shows there is martensite left in the part after cycling which is preventing full recovery in the austenite phase (just above A_f). This presence of non recoverable martensite (below M_d) is what may be used for the balloon expansion region of the stent.

          Figures 8-11 represent examples of various expandable configurations

15   (a = closed, b = expanded) which may be incorporated into the devices of this invention. The version shown in Figures 10a and 10b may be modified as shown in Figures 10c and 10d (closed and open, respectively) by omitting portions (indicated at 100 in Figures 10c and 10d) as to render the stent flexible for articulation. This may be done to other of the structures as well to improve flexibility.

20   Yet another version of a device incorporating the two component concept of the invention is shown in Figure 12. In this embodiment, a fragment of a stent 110 is shown. The stent includes a self-expanding component 112 and a deformable, external force expandable component 114. Self expanding component 112 may be resilient spring-like metal such a stainless steel or it may preferably be a

25   shape memory alloy in the austenitic state. Component 114 may be any deformable metal or the like such as annealed stainless steel or preferably a shape memory alloy in the martensitic state. The two components may simply be mechanically, welded or bonded together. Functions and operations are as described hereinabove.

          Referring to Figure 13 a version analogous to the embodiment of

30   Figure 12 is shown in which the two component concept is again embodied as different zones or portions of a single metal material.

As shown in Figure 13, a stent 120 (fragment showing) is of a self-expanding component 122 and a deformable component 124, both of which may be a single metal as spring steel or austenitic Ni-Ti which has been appropriately treated with respect to component 124 as by localized heat treatment or the like to alter the

5   characteristics of the material of the 122 component so as to render it deformable or martensitic, depending on whether it is merely resilient or is austenitic. Again, function and operation are the same as with other embodiments.

Referring now to Figures 14-16, a multi-strand braided stent is shown in Figure 15. Each strand 150 in the stent is a micro-cable. That is, each strand is

10   made up of a plurality of wires 152 and 154 as is seen in Figures 15 and 16. Each of the wires 152 and 154 consists of two different nitinol alloys as seen best in Figure 16, or one nitinol and one ordinary metal such as stainless steel, platinum or tantalum. The latter two would provide enhanced radiopacity. One nitinol alloy wire 154 has an austenitic finish (A_f) temperature less than body temperature. The other wire 152

15   could be nitinol having an A_s (austenitic start) greater than body temperature. Also, it could be an ordinary metal. Additionally, one or more of the strands may be of a biodegradable material such as a plastic or may be of a material including an absorbable drug.

Since the two alloys are stranded into micro-cable one does not have to

20   engage in selective, discrete heat treating methods to produce both shape memory and martensitic effects.

Radiopaque portions or coatings may be included on any parts of these stents as is known in the prior art.

While this invention may be embodied in many different forms, there

25   are described in detail herein specific preferred embodiments of the invention. This description is an exemplification of the principles of the invention and is not intended to limit the invention to the particular embodiments illustrated.

The above Examples and disclosure are intended to be illustrative and not exhaustive. These examples and description will suggest many variations and

30   alternatives to one of ordinary skill in this art. All these alternatives and variations are intended to be included within the scope of the attached claims. Those familiar with the art may recognize other equivalents to the specific embodiments described

herein which equivalents are also intended to be encompassed by the claims attached hereto.